SPECIAL ARTICLES.

STUDIES OF RAINDROPS AND RAINDROP PHENOMENA.

By WILSON A. BENTLEY. Dated October 1, 1904.

Our knowledge in regard to the mechanism of rain formation, i. e., the precise manner in which the nucleus of each raindrop is organized and the method by which the aqueous material is added to the nucleus during its growth, so that eventually raindrops of considerable size are produced, has hitherto been very unsatisfactory. Equally so is our knowledge of the actual altitudes within the clouds at which various rainfalls originate, the relative quantities of rain precipitated from different clouds and storms, the dimensions of the individual raindrops, and their variation in different storms and in different segments of the same storm. The desire to add, if possible, a little to our knowledge regarding rainfall phenomena led the writer, in the autumn of 1898, to undertake a systematic study of the various rainfalls occurring at his locality. This study was continued during the six following years—1899 to 1904, inclusive—up to the date of this writing.

I. METHODS OF OBSERVATION.

During this period hundreds of samples of raindrop impressions were secured, including raindrops emanating from various storms, clouds, etc. The method employed was to allow the raindrop to fall into a layer one inch deep of fine, uncompacted flour, with a smooth surface, contained in a shallow tin receptacle about four inches in diameter, which was generally exposed to the rain for about four seconds, although a longer time was given when the drops fell scatteringly. The raindrops were allowed to remain in the flour until the dough pellet that each drop always produces at the bottom of the cavity was dry and hard. These dough pellets, which were found by careful experiment to correspond very closely in size with the raindrops that made them,[1] were then extracted, labeled and, photographed, or kept on file for reference, together with the attendant meteorological data, such as temperature, height of clouds, kind of storm, etc. Though some of the large drops were somewhat flattened by their impact upon the flour (and the pellets thus made were similarly modified), yet, on the whole, this method of securing raindrop impressions and of ascertaining their relative dimensions proved very satisfactory.

The kind of storm, and the segment of the storm from which raindrops emanated, hour of the day, temperature, the kind and approximate height of clouds, their vertical dimensions, etc., and the occurrence or absence of lightning within the rain producing clouds directly over our locality were noted and filed with each sample of pellets. Some 344 sets of raindrop impressions in flour, each containing a large number of individual raindrops, were secured by this method from 70 different storms.

These samples portray the general character of the rainfall, as it occurred during the progress of 15 general rainstorms, 30 local showers and rains, and 25 thundershowers. A few of these samples represent merely isolated, incomplete cases, but most of them are complete sets and portray the character of the rainfall, relative size of drops, etc., throughout the whole cross section of a storm or shower, from the advancing to the receding edge. (See figs. 1 to 11. These photographs are the same size as the originals.) As our study progressed from year to year facts of much interest were brought to light, and, altogether, it proved very interesting and instructive.

[1] Drops of water about $\frac{1}{12}$ of an inch and $\frac{1}{6}$ of an inch in diameter, suspended from the end of a broom splint and from a glass pipette, respectively, were carefully measured, and then allowed to drop into flour from heights of from 12 to 30 feet. The smaller pellets ($\frac{1}{12}$ of an inch) were of so nearly the same diameter as the artificial raindrops that it was difficult to detect any difference, although in some cases the pellets were slightly flattened by impact, with a corresponding slight increase in the longer diameter. The larger artificial raindrops ($\frac{1}{6}$ of an inch) produced pellets that were considerably flattened and had a longer diameter, exceeding by about one-third the diameter of the drop. Singularly enough, they were more flattened than was often the case with pellets obtained from the large drops of actual rainfall.

II. DIMENSIONS OF RAINDROPS.

Perhaps the most remarkable fact, early brought to our notice, was the astonishing differences in the dimensions of the individual drops, both in the same and in different rainfalls. While the larger ones sometimes possessed diameters of $\frac{1}{4}$ and even $\frac{1}{3}$ of an inch, the smaller ones were but $\frac{1}{32}$ to $\frac{1}{50}$ of an inch in diameter, and the occurrence of microscopic drops too minute to make an impression in flour (whose dimensions were probably less than $\frac{1}{100}$ of an inch), was quite frequently noted. For the convenience of the reader, the various data have been compiled, so far as possible, in tabular form. The relative frequency of the occurrence of raindrops of various dimensions as they appeared in the 344 samples from the various storms is given in Table 1. In the tabular classification of the drops, the following approximate dimensions were used to designate each group. Those termed "very large" exceeded $\frac{1}{5}$ of an inch in diameter; those designated "large" were from $\frac{1}{7}$ to $\frac{1}{5}$ of an inch; "medium," $\frac{1}{16}$ to $\frac{1}{8}$ of an inch; "small," $\frac{1}{30}$ to $\frac{1}{18}$ of an inch; "very small," all whose diameter was less than $\frac{1}{30}$ of an inch.

TABLE 1.—*Number of samples, out of a total of 344, in which drops of various sizes were found.*

Size of drops.	Number.
Very small	149
Small	288
Medium	254
Large	141
Very large	35

As will be noted, the "small" and "medium" drops occur most frequently, each of them appearing in almost three-fourths of the samples, and next to them in the order of frequency come the "very small" and the large drops, each in nearly one-half of the samples. The very large drops were relatively rare, occurring in only 35 (or about one-tenth) of the samples. Although the small and medium-sized drops greatly outnumber the larger ones, it is to be noted that it does not follow from this that they furnish the bulk of the rainfall.

III. DISTRIBUTION OF DROPS.

In Table 2 the distribution of each of the various sizes of raindrops, or the number of occurrences within the various segments of rainstorms, is given. In compiling Table 2, only complete or nearly complete sets of raindrop samples were consulted, as was evidently necessary in order that the data should be homogeneous. These samples represent the distribution of raindrops within the various segments of 51 different storms, i. e., 9 general rainstorms, 23 thundershowers, and 19 rain showers.

TABLE 2.—*Distribution of drops of various sizes over 51 storm areas.*

Size of drops.	East edge.	East portion.	Central portion.	West portion.	West edge.
Very small	18	15	20	21	33
Small	37	41	46	32	32
Medium	30	42	42	40	27
Large	18	26	23	23	8
Very large	3	4	8	7	0

It appears that in general the very small drops increase in number from the east edge toward the west or receding edge of a storm, and that of the drops of other sizes, each, as a rule, shows a progressive increase toward the center of a storm, but then decrease toward the west edge. While this law of distribution seems to be true as regards the raindrops precipitated from the whole number of storms under consideration, the exceptions to it are not rare, especially as regards certain kinds of storms. As an instance in point, the data seem to strongly indicate that there is a paucity of large and very large raindrops within the central portion of the larger and older thundershowers, as compared with certain outlying portions. (See fig. 9, showing a photograph of a sample set of raindrops collected from a large and old thundershower.)

In general, the large and very large raindrops appear in much greater numbers and form a much greater percentage of the rainfall of the extra central, western, or receding storm segments than of that issuing from other segments. It seems to be a fact that, in general, showers renew themselves or acquire new vigor within the western or receding segments. It has been very frequently noted that the vast masses of low clouds (nimbus?), that might not inaptly be called "storm feeders," commonly existing within the central and western storm segments, attain to their largest dimensions therein. Indeed, they ofttimes attain to such vast vertical dimensions that their expanding summits reach up to and merge into the cirro-stratus crest canopy of the primary storm, until at last they develop and transform themselves into secondary showers, becoming heavy rain producers themselves, as annexes to the primary showers.

IV. INFLUENCE OF KIND OF CLOUDS.

Another aspect of our study, viz, the character and amount of the rainfall that emanates from different clouds and from various combinations of clouds, both when existing separately one above the other and when intermerging one with another in continuous vertical masses, is of great interest and has received a large measure of attention. In general, two or more cloud strata exist when rain is falling; from some varieties of clouds precipitation, at least in appreciable quantities, rarely or never occurs. If rain occurs when two distinct and widely separated cloud strata exist, it by no means follows that both of them are rain producers. On the contrary, it often happens that but one of them contributes rain or snow.

Table 3 gives the number of occurrences of raindrops of various dimensions as precipitated from different clouds and combinations of such one with another.

TABLE 3.—*Size of raindrops received from each kind of cloud.*

Kind of cloud.[2]	Size of raindrops.				
	Very small.	Small.	Medium.	Large.	Very large.
Cumulus alone, 30 samples	7	19	17	6	0
Nimbus or low stratus, 20 samples	14	12	4	0	0
Cirro-stratus, 33 samples	15	26	16	4	0
Cumulus and nimbus, 25 samples	19	25	20	4	0
Cirro-stratus and nimbus, 90 samples	43	58	48	20	1
Cirro-stratus and cumulus, 53 samples	10	36	44	26	11
Cirro-stratus, cumulus, and nimbus, 84 samples	30	82	84	80	23
Cirro-cumulus, 7 samples	3	5	2	0	0

[2] The term "nimbus" is here confined to low-lying clouds commonly seen in detatched masses scudding swiftly below higher clouds.

In analyzing the data of Table 3, perhaps the most important point clearly elucidated therein is the fact that (with one exception) all the "very large" raindrops and about three-fourths of the "large" ones emanated from compound cloud masses whose vertical dimensions were very considerable. It is worthy of note that all the data and observations seem to lead to the conclusion that, in general, the size of each individual raindrop depends largely, if not wholly, upon, and increases with, the square of the mass of upper and intermediate clouds that each drop passes through on its earthward journey.

The frequency of the occurrence of the various sizes of raindrops from various clouds, as given in Table 3, is most interesting and instructive. Considering it more in detail, we find that the simple low-lying cumulus clouds, the nimbus, the cirro-stratus, and cirro-cumulus, and the "cumulus and nimbus," produced no "very large" raindrops, and that these kinds of clouds gave altogether only fourteen samples containing drops classed as "large." It seems that practically the whole of the rainfall shed from these low and intermediate clouds consists of "very small," "small," and "medium" raindrops. See figs. 1 and 2 for photographs of raindrops shed from low nimbus and cirro-stratus clouds, respectively. The largest percentage of "very small" drops occurred in the samples of rain shed from low nimbus (or low stratus?) clouds. (See fig. 1.) These various clouds (except the cirro-stratus) represent practically all of the cloud forms that exist at low and intermediate altitudes, and the fact that they rarely shed raindrops of large size is very significant and instructive, and has an important bearing on theories hitherto generally accepted.

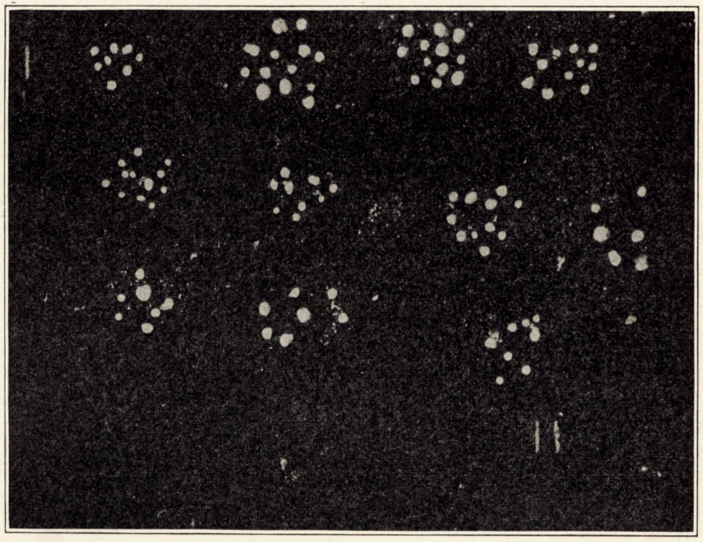

Fig. 1.—Raindrops from low nimbus clouds, taken at different dates.

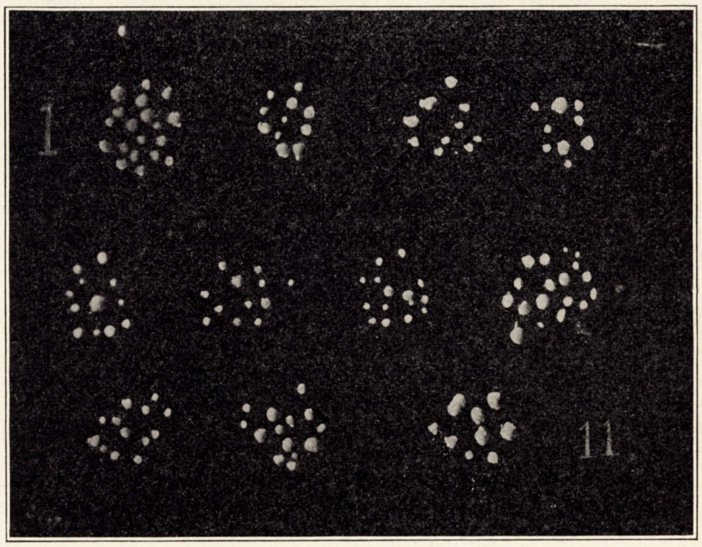

Fig. 2.—Raindrops from high cirro-stratus clouds, taken at different dates.

Analysis of the rainfalls of the high cirro-stratus alone, which are supposed to be due to the melting of snow crystals that issue from such clouds (see fig. 2), reveals the interesting fact that the raindrops, in general, correspond, as regards size, with the minute snow crystals that commonly issue from such high clouds in winter. "Small," "very small," and "medium" drops constitute the bulk of the rainfall of these lofty clouds. It would seem to be a fact that high clouds alone and low clouds alone, or, in fact, any clouds or combination of such lying and moving in horizontal strata, or possessing purely horizontal motion, are incapable of precipitating the large raindrops. These seem to be peculiarly the product of clouds that extend and move vertically. Often the high cirro-stratus clouds are associated with others lying at vastly lower levels, called the "nimbus" or, by some, "low stratus." This cloud combination, although occasionally present during showers, especially old ones, is yet peculiarly a general storm-cloud combination, and much the larger portion of the rainfall during general storms issues from such widely separated but associated cloud strata. The cirro-stratus, the upper component of this combination, exists at frigid altitudes, and almost certainly precipitates moisture only in the form of snow, while the nimbus, or lower component, with equal certainty sheds moisture only in liquid form, as minute raindrops. The larger raindrops are rarely shed from such clouds, though those of quite large dimensions sometimes are. Small to medium drops constitute the majority, though very small and microscopic drops are greatly in evidence. Photographs of raindrops shed from these associated general storm-cloud strata are given in figs. 3, 4, 7. Fig. 4 portrays the character of the rainfall during the progress of a general rainstorm from the far south—a West Indian storm, which was accompanied by lightning during its latter stages.

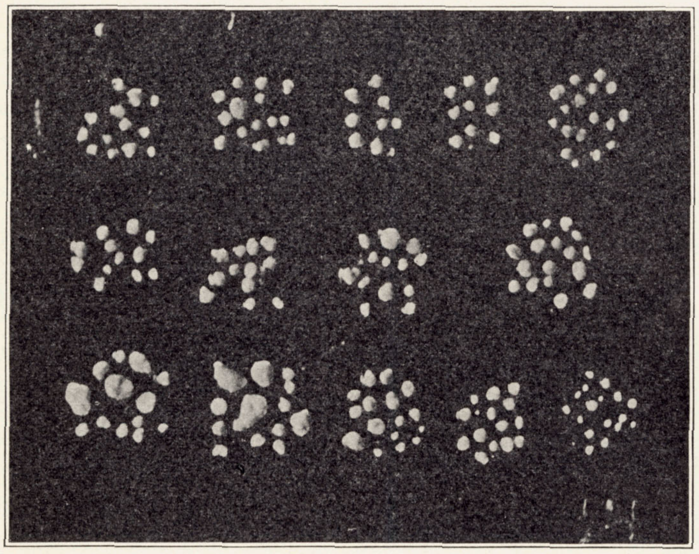

Fig. 3.—Complete set of samples from the great general storm of August 20, 1904. Duration of storm fifteen hours. One raindrop sample per hour was taken throughout storm.

Consider that portion of the data of Table 3 treating of the rainfall shed by higher, thicker, and more complex cloud masses. The combined intermerging cumulus and cirro-stratus are often heavy rain producers, and demand special consideration. The very large number of medium-sized drops present within the samples from these clouds is very noteworthy, as is, also, the considerable number of large and very large drops. These clouds, when so commingled, often possess great depth, and a large percentage of their proper motion, or expansive drift, is upward in a nearly vertical direction.

We now pass to a consideration of the rainfall shed from cloud masses possessing the maximum of thickness and complexity, i. e., the combined intermerging nimbus, cumulus, and cirro-stratus. See figs. 6, 10, and 11 for photographs of typical samples. This cloud combination, though occasionally met with in general storms, is peculiarly a thunderstorm-cloud combination. Such complex cloud masses often possess vertical dimensions of five or six miles, and occasionally attain, according to some observers, dimensions exceeding ten miles in thickness. Much of the expansion of such clouds, and especially is this true of newly formed showers, is exerted in a vertical direction, and a very large percentage of the moisture precipitated from them must, presumably, traverse through great distances of very dense mist or snow laden clouds before reaching earth. The character of the rainfall shed from such highly composite cloud masses is, as might be readily supposed, diversified, and each group or kind of raindrop is well represented. The large drops among the samples are almost as frequent as those of medium and small size. The very large drops form a much larger and the very small ones a much smaller percentage of the total rainfall than is usual.

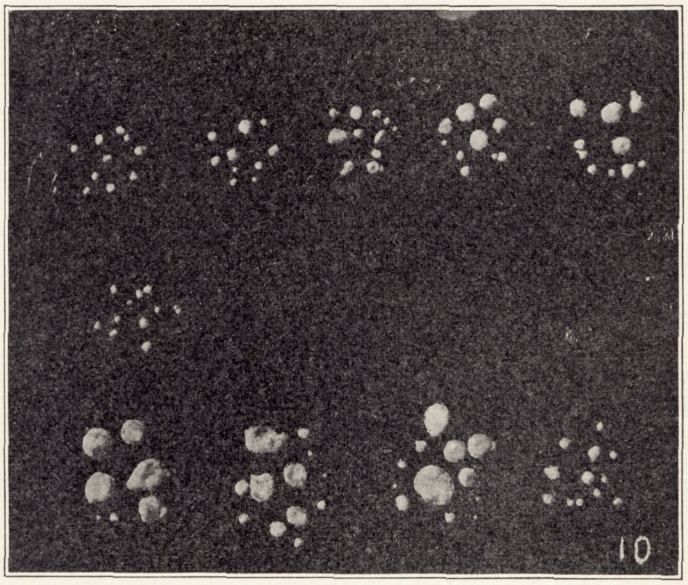

Fig. 4.—Raindrops of great West Indian general storm of July 9, 1899. Duration, sixteen hours. Sample taken throughout day of July 9, one sample every seventy minutes.

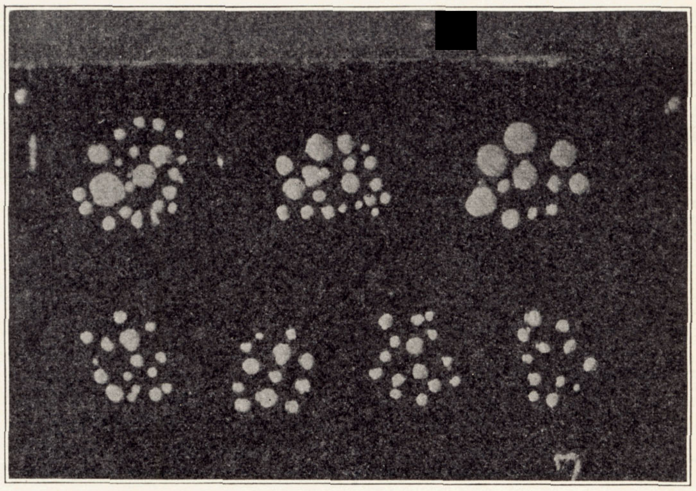

Fig. 5.—Raindrops of large and old thunderstorm of May 25, 1904. Duration, fifty minutes. One sample taken every seven minutes. Last four samples were from high cirro-stratus clouds.

For the reason that the larger raindrops are shed in considerable numbers only from thick, vertically expanding, complex clouds of this character, we may infer that the larger raindrops, whenever produced, are those that originate highest above the earth, and presumably as snow. From this it follows that whenever the rainfall consists wholly or partly of such large drops, the presence of vast vertically extending cloud masses is almost certainly indicated. This fact should possess much value in connection with cloud study and other meteorological work, because it enables us to quite certainly determine the presence or absence of such thick cloud masses within the various segments of storms, when their existence can not otherwise be ascertained by direct vision, owing either to the presence of dense masses of low clouds, or to the thickness of the rainfall.

V. STUDY OF THE INITIAL RAINFALL.

The first rainfall or precipitation that occurred from newly formed or forming showers received particular attention, because it must reveal the character of the rainfall resulting from the initial efforts of the rain-producing agencies and also because of its unusually large percentage of very large and large drops. These large drops give ample demonstration of the unusual vigor with which these initial rain-making operations are carried on. For photographs of typical sets of raindrops of newly formed thundershowers see figs. 8 and 11.

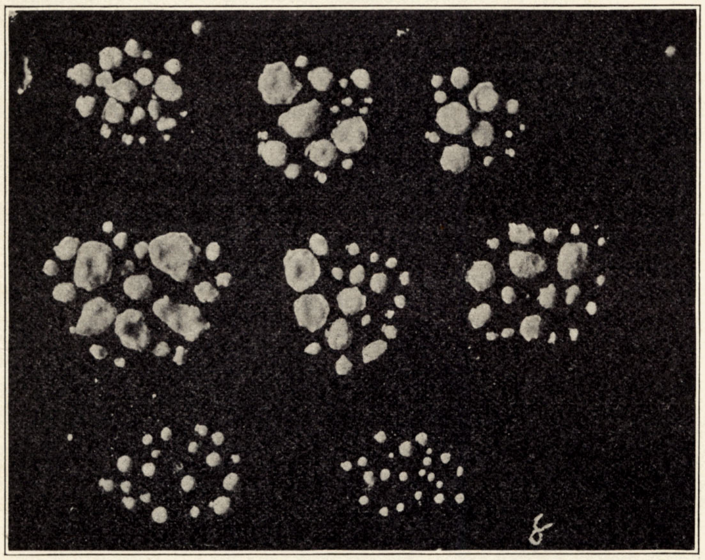

Fig. 6.—Large thundershower raindrops of September 20, 1904. There were dense, low, nimbus clouds throughout this shower. Duration, one hour. One sample taken every seven minutes.

The unusual character of such rainfalls is well shown in Table 4, and by the photographs. The large and medium sized drops appear in even larger numbers than do those of smaller denominations. The "very large" ones occur in one-third of all samples, while the "very small" ones are almost unrepresented.

TABLE 4.—*Relative frequency of the appearance and distribution of the drops within the various segments of newly formed showers. Eight different rainfalls, 45 samples.*

Size of drops.	Segment of storm.					
	East edge.	East portion.	Central portion.	West portion.	West edge.	Total.
Very small	1	1	0	3	1	6
Small	5	8	6	8	8	35
Medium	7	8	8	8	8	39
Large	4	8	8	6	5	31
Very large	2	4	2	6	1	15

VI. LIGHTNING AND RAINDROPS.

The character of the rainfall in connection with the occurrence of lightning received, during our study, a large measure of attention. The endeavor was made to ascertain whether any connection actually exists between the raindrop dimensions, the copiousness of the rainfall, and the presence or absence of lightning.

The first column of Table 5 gives the general character of the rainfall, as shown by the 76 samples obtained during the progress of 25 thundershowers. It is to be noted that when these samples were taken the lightning occurred directly overhead, as distinguished from that occurring at a distance.

The unusually large percentage of the numbers of occurrences of "large" and "very large" raindrops will be noted, and is very significant and instructive. It was frequently noted that whenever the electric discharges were unusually frequent and powerful the rainfall was unusually thick and heavy, and consisted of raindrops of all sizes, the larger ones predominating.

It was thought best, in view of the importance of this subject, to compare this with similar data from other rainfalls unaccompanied with lightning and also with data from thundershowers in which the electric discharges occurred at some distance away from that portion of the shower that furnished the raindrop samples. To this end, a similar number of samples, i. e., 76, from each of these kinds of rainfall was examined, and this data is also shown in Table 5.

TABLE 5.—*Size of raindrops during lightning.*

Size of drops	Storms with lightning overhead.	Storms with distant lightning.	Storms without lightning.
Very small	15	31	38
Small	61	67	70
Medium	64	63	57
Large	58	23	22
Very large	23	3	1

The data here given afford good ground for the belief that a connection actually does exist between the dimensions and relative frequency of the raindrops and the occurrence of lightning. It may be added that, irrespective of direct raindrop testimony, this conclusion is very strongly supported by a number of independent observations of the portions of the clouds wherein the electric discharges originate. In general the latter were observed to originate within (as distinguished from merely passing through) the thickest and densest portion of each shower under observation, and it was quite certain that from this portion the heaviest rainfall and largest drops were being precipitated. Lightning seems rarely to occur when the raindrops fall scatteringly; although in such cases the drops are almost invariably of very large size.

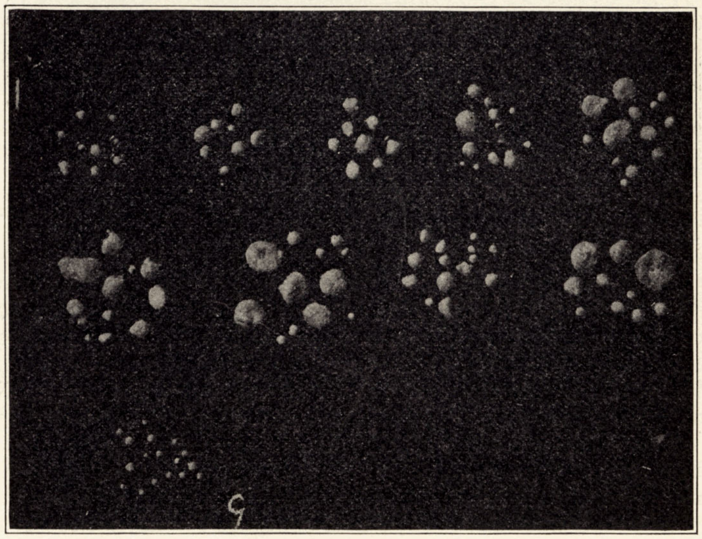

Fig. 7.—Samples from general rainstorm. Taken in 1899.

Touching this point (thickness or thinness of the rainfall) the testimony of the raindrops of the 76 samples secured when lightning was directly overhead is of interest. Our notes show that the rainfall was very thick and heavy as regards 33 of them, was moderately thick and copious as regards 31 of them, and was thin or scattering in only 13.

As is well known, electricity, or electric charges, exist upon, or confine themselves to, the surfaces of objects, as snow crystals, raindrops, etc. It may well be that the cause of lightning, or rather the causes that operate to impart excessive electric charges to the raindrops, the collective discharging of which produces the phenomenon of lightning, may be largely due to processes in operation far up within the clouds, where congelation and crystallization take place. Snow crystals are frequently, if not invariably, highly charged with electricity. Moreover, such crystals and granular snow nodules possess enormously large surfaces, as compared with their bulk. Their conversion into raindrops would enormously reduce the surface area of the transformed, consolidated aqueous mass, and would accordingly transfer and concentrate upon a single vastly smaller globular surface, i. e., the surface of a single large raindrop, the charges formerly disseminated over the surfaces of one or perhaps a large number of snow crystals, or flakes of snow, or granular snow pellets. It is quite conceivable that the larger drops, at least, may often receive in this manner electric charges far in excess of what they can retain, and especially may this be true, when, in addition, they receive supplemental charges by overtaking and merging with smaller drops while falling. In this connection, it is of interest to state that the few instances on record (in autumn and spring) when the snow from thundershower clouds, owing to the relativaly low temperature, descended unmelted to earth, so that its character reveals itself, it was found to consist of large pyramidal-shaped granular snow pellets.

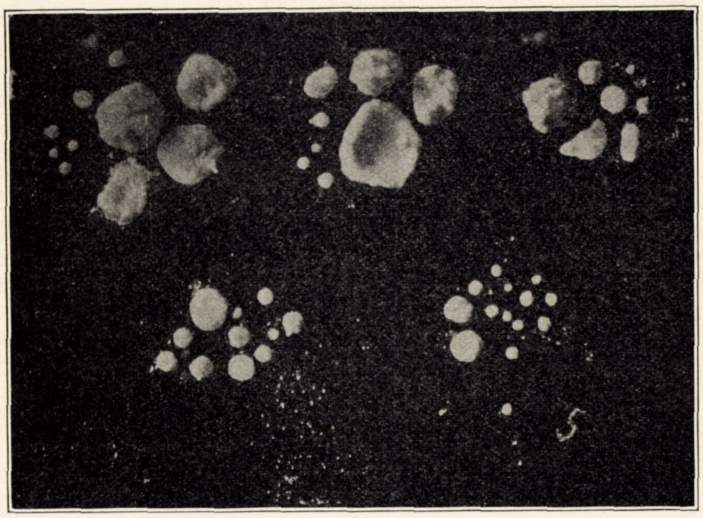

Fig. 8.—Rather small, newly formed, thunder and hail shower. July 1, 1904. Duration, fifteen minutes.

It is to be noted that the surface area of a given mass of aqueous material in the form of mist drops is enormously reduced merely through its conversion into granular snow, because granular snow itself is formed through the condensation of myriads of minute rain or mist drops upon snow nucleii, and their subsequent conversion thereon into ice by freezing.

Concerning the many minor phenomena connected with the formation and precipitation of rain, one that is of considerable interest and at times seemingly inexplicable is the descent to earth (often simultaneously with vastly larger drops) of great numbers of exceedingly minute microscopic raindrops, presumably less than $\frac{1}{100}$ of an inch in diameter, and so very light that they descend quite slowly. This phenomenon, which occurs during very violent, as well as during gentle, rains and showers, would seem to furnish reasons for supposing that the air directly beneath such showers does not move violently upward and enter the vortex of such storms. It is obvious that if it did it would buoy up, or carry upward with it all such light minute raindrops, and prevent their descent to earth. The inference seems plain that the warm, moisture-laden, inflowing lower air that supplies such storms with fresh quantities of moisture is drawn from some distance away from, and around them, and undergoes its initial expansion before it reaches the near vicinity of such storms, and hence flows into them as somewhat elevated, horizontal, converging air currents.

VII. WEARING AWAY OF RAINDROPS WHILE DESCENDING TO EARTH.

A factor of some importance, though perhaps not often considered, is the erosive and evaporative action upon the falling raindrops or snow crystals of the relatively dry and cloud-free air spaces between two clouds, or, more particularly, between cloud and earth. Each raindrop doubtless loses appreciably through this cause, and (barring collisions and merging with its fellows) is somewhat smaller when it reaches the earth than when it first left the clouds. The percentage of loss that each raindrop undergoes must obviously vary from time to time, with varying conditions. As is well known, raindrops of considerable size are sometimes completely evaporated while passing through warm, dry air, and fail to reach the earth. Such phenomena are sometimes noted over desert regions, where considerable rainfalls may be dissipated in this manner. Reasoning from the foregoing, and from other observed facts, it seems quite certain that rainfalls consisting of microscopic drops may quite often be shed from large cumulus and other clouds (although of course in minute quantities only) and yet fail to come under our observation, because reabsorbed while on their earthward journey.

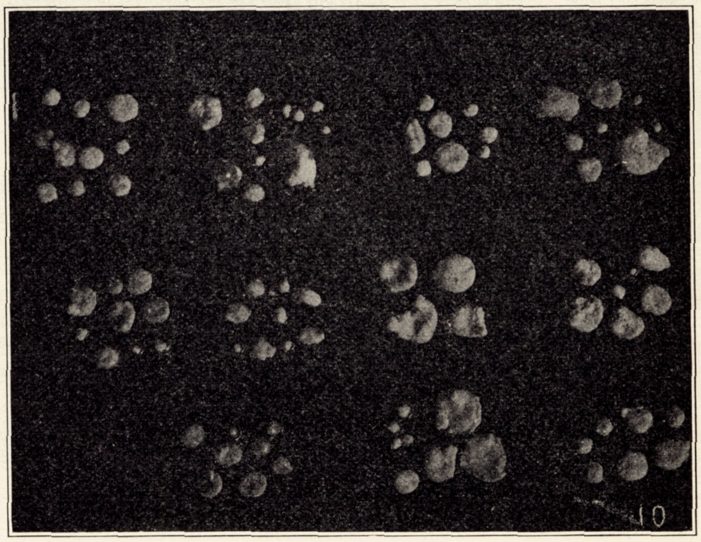

Fig. 9.—Thundershower raindrop samples. Taken in 1899.

A phenomenon of much interest and significance, and one that would seem to nullify some accepted theories, is the occasional occurrence of rainfalls consisting entirely of drops of nearly uniform size. The drops are sometimes of large and sometimes of small dimensions, and they have been seen to fall both thickly and scatteringly. Although not common, yet rainfalls of this character, and particularly isolated samples, taken at one time and another during various rainfalls, are far from rare; 26 samples, among our total of 344, were of this character. Two of these consisted of very small drops, nine of small drops, ten of medium drops, and five of large or very large drops. In addition, many samples (though not so classed) consisted almost wholly of uniform drops. It seems impossible to conceive of any combination of circumstances or action of natural forces, whether by liquid merging, condensation, or otherwise, by which all the myriads of small raindrops which, according to the theory of liquid merging, must fill the cloud spaces and regions far below them, could be drawn, forced, or merged together, and incorporated within the uniform sized raindrops, so that the latter only would be left to fall to earth. We seemed forced to the conclusion that such uniform sized drops, and especially the larger of these, are due to the melting of snow crystals or granular snow. As is well known, snowfalls often occur in which the individual crystals, or granular snow pellets, are of practically uniform dimensions.

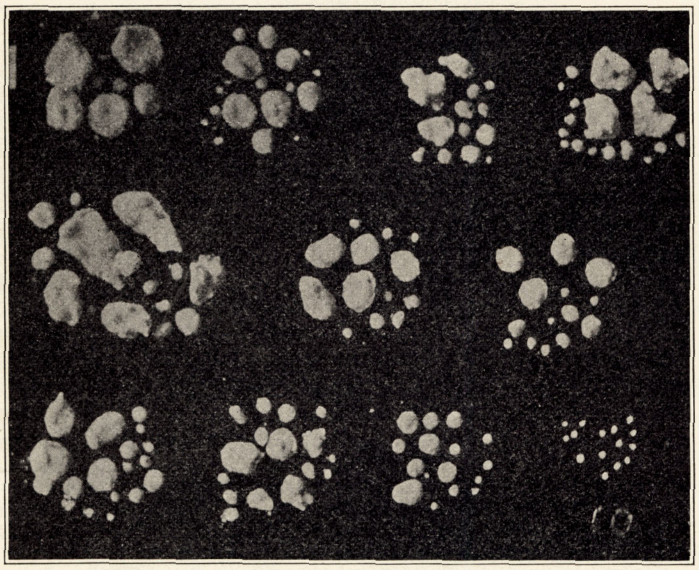

Fig. 10.—Great thundershower of September 3, 1904. Shower was accompanied by vivid and frequent lightning. Duration, one hour. One sample taken every five minutes.

VIII. DUAL ORIGIN OF RAIN.

In view of all the facts and data at hand, we seem to have the best of grounds for assuming that rain often has a dual origin; that there are, in general, two distinct processes concerned in the formation and precipitation of rain, or of snow from which rain ultimately results. These processes might not inaptly be termed the fluid and the solid (or crystalline or snow) processes. Though each of these processes may and doubtless often does precipitate moisture independently of the other, more frequently they unite and aid or supplement each other in the work of rain making. Granting the truth of this "dual" theory of rain formation, all the seemingly inexplicable phenomena connected with the formation and precipitation of rain, such as the manner of the growth of raindrops and their attainment to a large size, the formation of uniform sized drops and of large, scattering drops, the occurrence of perpetual snow upon the summits of isolated peaks, even in the Tropics, etc., become plain and are easily and completely explained. It now becomes of much interest to ascertain which process performs the major part of the work of rain making. Our present knowledge regarding this point is yet incomplete, but the data so far collected, as well as the inferences to be drawn from well-known general facts and considerations, point strongly to the conclusion that the crystalline or snow process performs the major part. Reasoning from the well-known laws governing the precipitation of solids from a fluid or liquid medium, it is obvious that the lower air (which, it is to be noted, contains the bulk of the moisture within the atmosphere) can not, in general, precipitate large quantities of moisture in the form of rain or snow until it is carried upward to considerable heights, and is greatly cooled thereby. Almost invariably, while showers and rainstorms are in progress, extensive air spaces exist between cloud and earth that are, by nature of their relatively higher temperatures, actually dry and vapor thirsty. Usually these air spaces are from 3000 to 5000 feet thick and free of clouds of any kind. Such cloud-free air spaces do not even hold all the moisture they can hold in solution in an invisible state, as otherwise clouds would inevitably form and fill the whole space between cloud and earth. The base of the lower cloud strata is merely the boundary, the meeting point, of two volumes of air, the upper of which is over saturated, and becomes more so with increase of altitude; the lower one is not saturated with moisture and becomes progressively drier (because its temperature increases) as the earth is approached. Obviously, then, at the base of the clouds (and for some distance upward) the air does not contain much more moisture than it can hold in an invisible state, and, accordingly, is far from being in a condition to precipitate large amounts of rain or snow.

We may rightly conclude that the rainfall shed from such low clouds consists wholly of small raindrops, and is in inconsiderable quantities. From this it follows that we must look to altitudes much more lofty for the source of those enormous quantities of water that often fall during our heavy rainfalls. This region of what we might term maximum precipitation may be assumed to vary greatly in altitude according to time of year, violence of storm, etc., but, in general, its altitude must be so great that it is quite certain that much, probably the the major part, of its moisture is precipitated in the form of snow. Since particles of moisture precipitated within this region and within the summit portions of the storm clouds are colder than those of lower cloud levels, and have an opportunity of collecting cloud and mist particles throughout the whole vast extent of the clouds below them, they must ultimately attain to much larger size than those from lower regions, and can thus be distinguished from them. Assuming, accordingly, that the larger raindrops issue from the upper portions of the clouds and are due to the melting of snow, or, conversely, that the smaller ones originate by liquid processes alone within the lower clouds, we have a means of approximately ascertaining which process produces the major part of the rainfall. We have only to group together the individual raindrops (flour pellets) within the samples secured during various rainfalls, and weigh each group separately. Samples containing 244 individual raindrops from four typical thunder clouds were used for this purpose. The number of large and very large drops within these four samples numbered 63, and weighed 26 grains, troy. The number of medium, small, and very small raindrops numbered 181, and weighed 11 grains, troy. Assuming these respective groups, and weights, to approximately represent the portions of the rainfall due to the melting of snow, and to purely liquid processes, it would seem that the major portion of the rainfall of thundershowers is of a snow origin.

Regarding the rainfall of general storms, the portions of the rainfall respectively due to the melting of snow, and to liquid processes alone, are most difficult of estimation, because often a portion of such rainfall, although consisting of small raindrops, emanates from the high cirro-stratus clouds, and is almost certainly due to the melting of minute snow crystals. However, the bulk of the rainfall usually emanates from certain circumscribed portions of such storms, and this major portion (heaviest rainfall) often consists of large, medium, and small raindrops, and approaches in character somewhat closely to that shed from thundershowers. Moreover, the clouds within such portions of general storms are often thick and extend upward to vast heights, and the places of origin of the various denominations of raindrops within them are probably not very different from those of thundershowers. For comparison, four samples of raindrop pellets from general storms, taken during heavy rainfalls, were consulted, and the drops grouped, divided, and weighed in the same manner as in the case of the thundershower samples. The four samples contained 205 raindrops. But ten of these were of large size, though there were 46 of medium size. The number of small and very small drops numbered 149.

Fig. 11.—Great thundershower, newly forming, of August 14, 1904. This shower was accompanied by vivid and frequent lightning, and underwent many partial intermissions and renewals. Duration, fifty-five minutes.

The large and medium drops were grouped into one class, and the small and very small into another, and weighed. The former weighed 6 grains, troy, the latter 4 grains, troy. This would seem to indicate that the major portion of the rainfall, even during general rainstorms, emanates from great heights, and is probably traceable to snow origin. It is true that in making these estimates no allowance has been made for the liquid raindrops and aqueous material that, through merging and other processes, were probably added to and incorporated with those classed as of snow origin. This may sometimes, and in some instances, be considerable. But after making all due allowances for this and other uncertainties, the fact remains that the very large and possibly the major portion of the rainfall in all climes is due to the melting of snow flakes or granular snow. As having a bearing on this point, it may be well to quote Mr. Maxwell Hall, of Jamaica (see MONTHLY WEATHER REVIEW for May, 1904, page 230). Mr. Hall, referring to the expansion of the cumulus clouds and the conversion of their summits (while mushrooming out) into cirro-stratus clouds, says: "By means of a sextant it was found that the average heights of such well-formed rain producing cumuli was as much as six miles. At this elevation the temperature is below zero, and strato-cirrus must consist of fine snow. This fine snow ultimately falls by its own weight, and, melting, produces those gentle after rains that follow the heavy rains and squalls of the (central) cumulus." The photographs of thundershower raindrops in figs. 5 and 6 illustrate the general character of the rainfall of such showers as Mr. Hall describes. Groups 1 to 3 of fig. 5, and 1 to 6 of fig. 6, are typical of the heavy rains of the central cumuli, while 4 to 7 of fig. 5, and 7 and 8 of fig. 6 are typical of the gentle rains due to the melting of the snow crystals shed by the cirro-stratus clouds, such as Mr. Hall mentions. Sometimes such striated cirro-stratus clouds assume curious rounded flocculent shapes or convolutions, their under sides seeming, in fact, to bulge downward in places, and groups 4 to 7 of fig. 5 possess unusual interest, as they fell from flocculent, bulging, cirro-stratus clouds of this character.

In conclusion, it seems hardly necessary to add that the mechanism of rain formation and the phenomena connected therewith is of great interest and import, and should receive from scientists a larger measure of attention than hitherto.

It seems certain that systematic study of this and allied phenomena would, through the increase of our exact knowledge regarding it, richly repay patient and thoroughgoing investigation. Aerophiles, containing self-registering instruments, might, with advantage, be sent up into the clouds during various rainfalls, and the messages they would bring down would doubtless greatly increase our knowledge of the temperatures, humidity, electrical conditions, etc., of that mysterious cloudland realm, so rarely entered and of which we know so little. As yet we know not to a certainty the exact heights of the various rain-producing clouds or strata, or how far within the clouds above their bases precipitation first commences. Neither do we know the temperature or humidity within the various "lows" and "highs," or within thunder and storm clouds, nor the variations of these with corresponding altitudes within cloud-free regions outside storm areas. Our knowledge of the highest altitudes attained by the upper clouds within the various segments of general rainstorms is most unsatisfactory, and we know but little of the ultimate maximum altitudes to which water vapor ascends.

As Professor Abbe says, referring to recent balloon ascents in Europe, when heights of 10,000 to 20,000 meters were attained (MONTHLY WEATHER REVIEW, June, 1904, pp. 276–277):

> The air that descends in our areas of high pressure and that which flows out of the polar regions may come from the upper limits of the atmosphere, and with equal probability the air that ascends in our areas of low pressure may continue its journey upward to those same heights. * * * We at the bottom of the atmosphere are nearly as unconscious of the commotion above us as are the animals at the bottom of the ocean.

THE ADVANCEMENT OF METEOROLOGY.

By T. H. DAVIS.

In Prof. J. M. Pernter's letter, which appears in the May issue of the MONTHLY WEATHER REVIEW, there are two paragraphs that all sincere meteorologists should "read, mark, learn, and inwardly digest." Speaking on the discovery of the correct physical basis, he states:

> This basis will never be discovered by means of experiments in predictions, which are, for the most part, matters of personal judgment, but only *through long-continued, rigidly exact, genuine research*, with the aid of physical methods, by men equipped with a complete knowledge of physical, meteorological, and mathematical sciences.

Again he states:

> Work, hard and thorough work, for many years, and not a game of chance in experimental predictions, is what is required in this matter.

Scattered through the United States are a number of stations for the regular observations of meteorological phenomena. These are in charge of trained men, who regularly make observations of temperature, pressure, humidity, wind (direction and rate of travel), conditions of weather and so on, as directed by the Central Bureau in Washington. To these clever, educated men this work, speaking generally, must after a time become quite mechanical, and they must feel, after recording their observations, producing weather maps, and replying to numerous telephonic inquiries throughout the day, that those duties are all that is required of them, and really they should be, because they are more arduous than is generally supposed. For this reason it is only now and again, at long intervals, that we see any special investigation reported as having been made by any of the weather observers.

Now, all who are truly interested in meteorology possess an ardent desire to see it included in the realms of the exact sci-